

## **Characterization and Modeling of the Philippine Archipelago Dynamics Using the ROMS 4DVAR Data Assimilation System**

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### **LONG-TERM GOAL**

The long-term goal of this project is to improve our capability to predict the inherent spatial and temporal variability near the Philippine Straits, and thus contribute to the development of reliable prediction systems.

### **OBJECTIVES**

The primary focus is to provide a comprehensive understanding of the remote and local factors that control the meso- and submesoscale features in and around the Philippine Archipelago Straits. The main objectives are:

- to explore the effects on the Philippine Straits of remote forcing from the equatorial waveguides, throughflows, and adjacent seas mesoscale dynamics;
- to estimate the effects of local winds in generating meso- and submesoscale variability;
- to quantify the role of barotropic tidal forcing in promoting side wall eddies and internal tides;
- to study the role of abrupt changes in bathymetry in generating submesoscale variability; and
- to investigate the impact of variational data assimilation on the simulation and predictability of the meso- and submesoscale circulation features.

### **APPROACH**

The approach for achieving the proposed goal and objectives is via model simulations using ROMS

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(Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009) and its comprehensive ocean prediction and analysis system (Moore *et al.*, 2004, 2009, 2010a,b,c). Tidal forcing is imposed using available global OTPS model.

ROMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009). The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgrid-scale parameterizations (Durski *et al.*, 2004; Warner *et al.*, 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom. Several adjoint-based algorithms exist for 4-Dimensional Variational (4D-Var) data assimilation (Moore *et al.*, 2010a,b,c; Powell *et al.* 2008; Muccino *et al.*, 2008; Di Lorenzo *et al.*, 2007), ensemble prediction, adaptive sampling, circulation stability (Moore *et al.*, 2004), and sensitivity analysis (Moore *et al.*, 2009).

Two regional, nested grids have been built: coarse (5 km), and fine (2 km). The initial and lateral boundary conditions are from the 1/12° global HYCOM with NCODA (provided by Joe Metzger and Harley Hurlburt) and 1/4° global Mercator with data assimilation (ORCALIM025), atmospheric forcing is from NOGAPS 3-hours, half-degree resolution, and the tidal forcing is from the global OTPS model.

## WORK COMPLETED

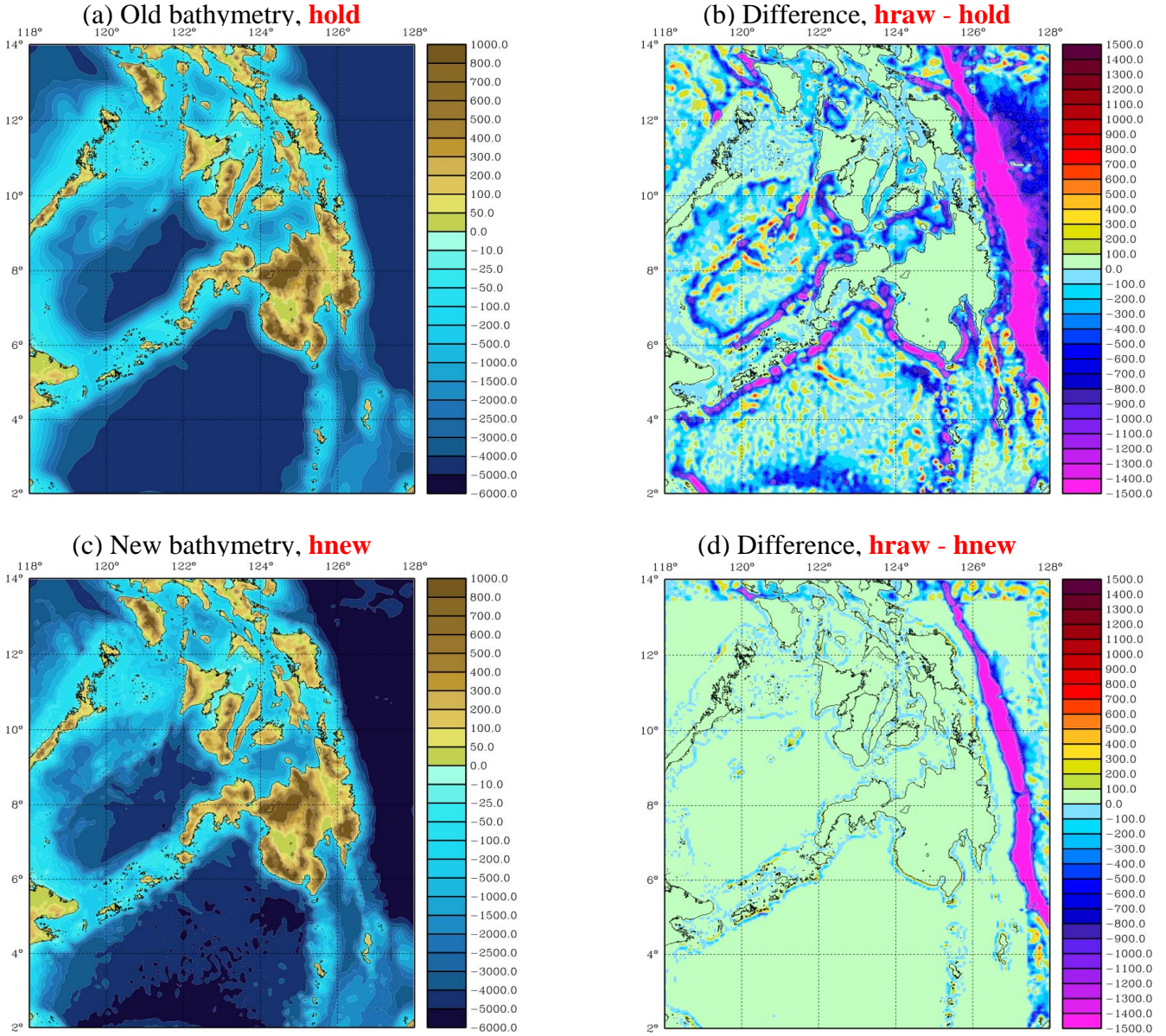
Real-time forecasts without data assimilation in the Philippine Archipelago were carried out in support of the *Exploratory* cruise (June 2007), *Joint* cruise (December 2009), *Regional IOP-1* cruise (January 2008), and *Regional IOP-2* cruise (February-March 2009). Each prediction cycle, updated daily, was run for 9 days (4-day hindcast and 5-day forecast). The model was initialized 4 days prior to the forecast cycle starting day to use reanalyzed atmospheric and boundary forcing. Real-time forecasts can be found at <http://www.myroms.org/philex>.

A tidal harmonic analysis on free-surface and currents was carried out to validate and compare ROMS against OTPS fields. The results show that the barotropic tides are well simulated in ROMS except in the interior of the Philippine Archipelago for the 5km grid. This is improved in the 2km grid indicating that finer resolution is needed to resolve the inter-island passages. This analysis was also used to study the structure and generation mechanisms of internal tides. We found that internal tides are generated in the Sulu islands chain and propagate in both directions towards the Sulu Sea to the north and the Celebes Sea to the south (Zhang *et al.*, 2010).

As a preamble to the data assimilation experiments, optimal perturbations and adjoint sensitivity analysis were performed to identify the validity of the tangent linear approximation, assimilation time windows, and observational operators. Three different adjoint sensitivity metrics have been computed for the Mindoro, Bohol, Surigao, and San Bernardino Straits. They are: transport, velocity anomaly, and temperature anomaly. Results indicate that bathymetry, temperature and velocity are crucial to obtaining a good estimate of transport.

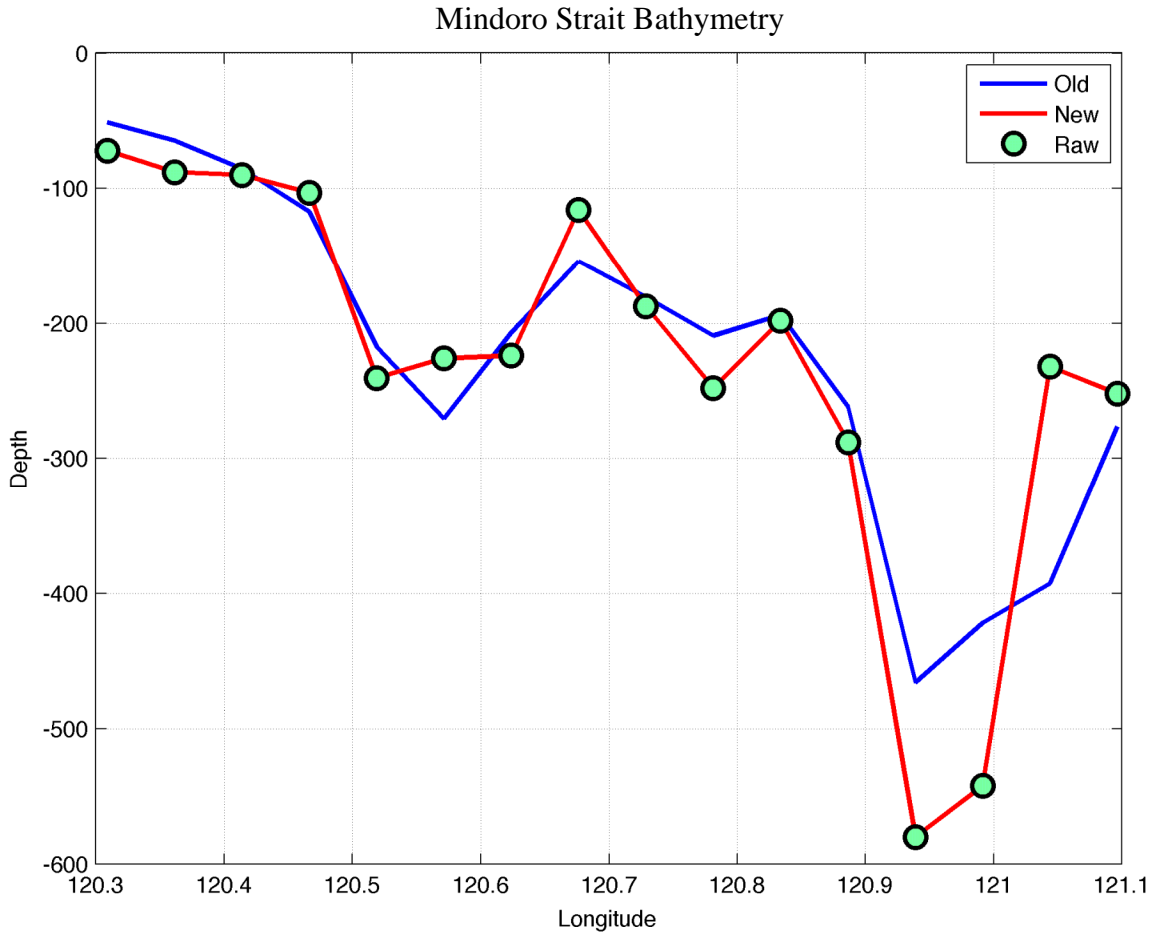
## RESULTS

Numerical modeling in the Philippine Archipelago is challenging for any global or regional ocean model due the complex bathymetry which includes numerous islands, passages, and several semi-enclosed basins and seas, as shown in Figure 1.



**Figure 1. ROMS model bathymetry (m) for the 5km horizontal resolution grid: (a) old smoothed bathymetry, **hold**, (b) difference between raw and smoothed bathymetry, **hraw - hold**, (c) new smoothed bathymetry, **hnew**, (d) same as (b) but for **hraw - hnew**.**

The smoothed bathymetry used in the 5km and 2km regional PhilEx grids were improved in an effort to get more realistic configurations and throughflows across the inter-island passages. Figure 1, shows the old (panel a) and new (panel c) model smoothed bathymetry for the 5km horizontal resolution, denoted **hold** and **hnew** respectively. It also shows the difference between the raw and smoothed bathymetry (panels b and d). The raw bathymetry, **hraw**, is interpolated from the ETOPO2 dataset, which has a 2-minute longitude/latitude resolution. Then, **hraw** is smoothed with a second-order Shapiro filter (Shapiro, 1975) to remove the small-scale noise. Since ROMS has terrain-following vertical coordinates, **hraw** is further smoothed to suppress systematic computational errors in the discretization of the horizontal pressure gradient force (Shchepetkin and McWilliams, 2003). There are various methods to smooth bathymetry in ocean models. The methods used here are discussed in Dutour et al. (2009). The smoothed **hold** bathymetry is obtained by successive applications of a one-dimensional, second-order Shapiro filter until a target slope factor (also known as **r**-factor) is reached (**r** = 0.25). There are several variants for this technique but none of them preserve the *a priori* volume of the basin. In the complex bathymetry of the Philippine Archipelago, it can substantially change the sill depths between island passages, as shown in Figure 2 (blue curve) across the Mindoro Straits.



**Figure 2. Model bathymetry (5km grid) for the Mindoro Strait. It shows the bathymetric profile between Mindoro and Busuanga islands (across 12.147°N) for the **hold** (blue curve), **hnew** (red curve), and **hraw** (green circles) bathymetries.**

A new smoothed bathymetry, **hnew**, was created using the linear programming (LP) method proposed by Dutour *et al.* (2009). This method allows several constraints in the smoothing minimization like preserving the bathymetry in certain grid cells (like on the continental plateau), maximal amplitude modification, desired slope and steepness (**r**-factor), land/sea masking, and more importantly preservation of volume.

The difference between the **hold** and **hnew** bathymetries is substantial when compared with the **hraw** values from ETOPO2, as shown in Figure 1. The **hnew** bathymetry shows a lot of more structure everywhere across the inter-island passages and the semi-enclosed Celebes and Sulu Seas. All the passages and straits look more realistic. Only the Mindoro Strait is shown here (Fig. 2), but the same applies for the Sibutu Passage, Dipolog Strait, Surigao Strait, and San Bernardino Strait. At the Mindoro Strait the values of **hnew** (red curve) are indistinguishable from **hraw** (green circles). Notice that the sill depth in **hold** is shallower and the strait is wider.

There are still some vast differences in the Pacific Ocean when comparing **hraw** to **hnew** (Fig. 1c). This is primarily due to a 5-10 km shift in the continental plateau. This was ignored because it does not affect the circulation within the Philippine Archipelago.

The linear programming approach is far superior but it requires several trials before the optimal bathymetry and behavior is achieved. The model needs to be tested and evaluated for errors in the horizontal pressure gradient. Also since the bathymetry is steeper and realistic, the model requires a smaller time step for stability. Several six-month runs were carried out to test the new bathymetry, **hnew**.

The next issue that was addressed in the simulations for the Philippine Archipelago was to try a different dataset for lateral boundary conditions. We observed excessive water property modifications with depth when the HyCOM daily fields were used to provide lateral boundary conditions to the 5Km grid. There is a tendency in ROMS to over-mix the entire water column due to unstable forcing at the open boundaries. This water modification deteriorates the solution after 2-3 weeks beyond the data assimilation and new data is needed to correct for the over-mixing. This causes the memory of data assimilation to be lost.

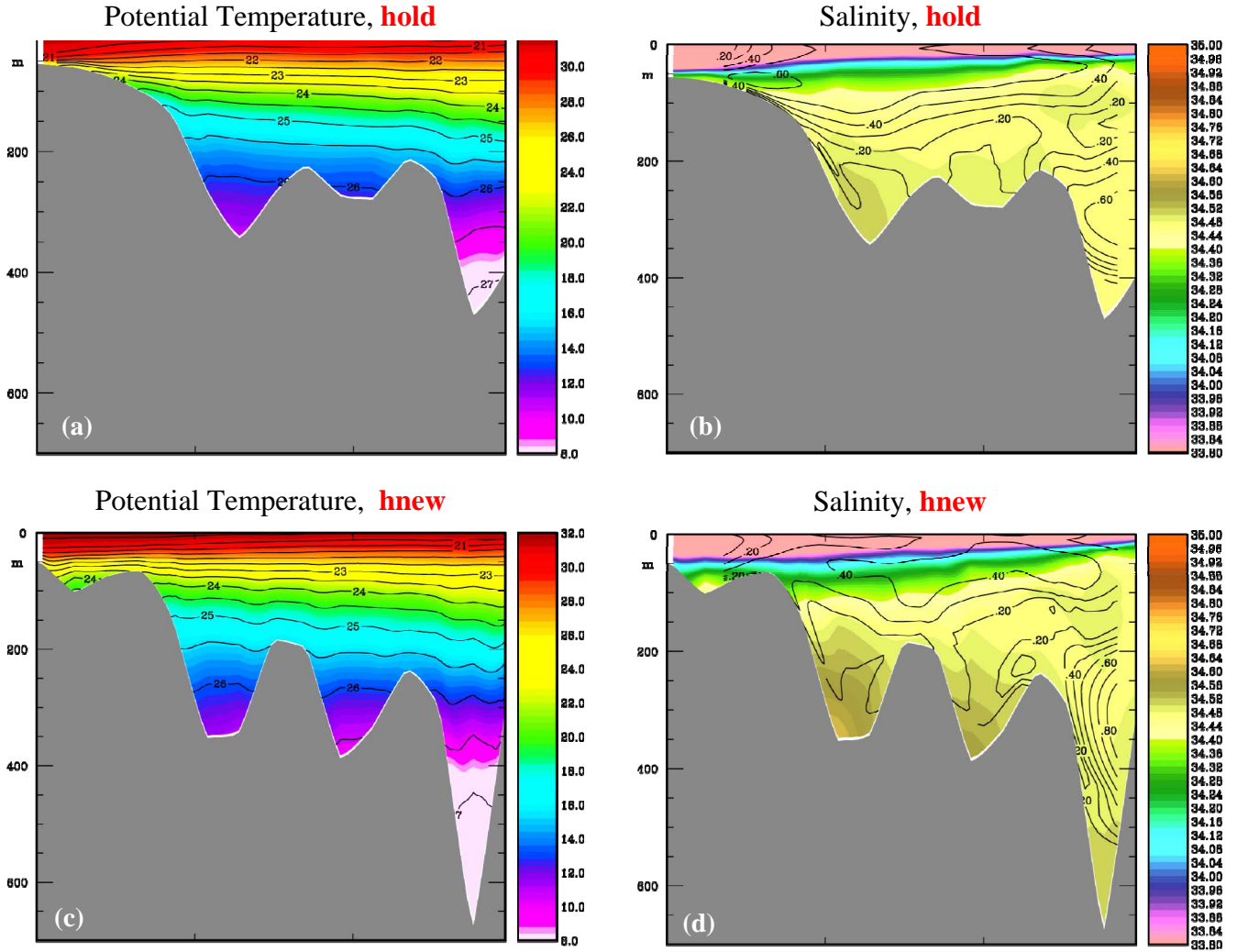
We are now using global 1/4° resolution Mercator daily fields as open boundary conditions. The Mercator fields are much coarser than the ones from HyCOM but have better T/S properties in deep water. Figure 3, shows a cross section of temperature and salinity across the Mindoro Strait for time-averaged August 2007. Figures 3a and 3b show the solution when **hold** is used, whereas 3c and 3d is the solution with **hnew**. Clearly, the solution using **hnew** is more realistic and shows a well-defined throughflow (velocity magnitude contours in the salinity section). The throughflow is not as intense in the **hold** case; it is constricted because of the shallower sill depth.

## IMPACT/APPLICATIONS

This project will advance our scientific understanding of the generation dynamics and predictability of meso- and sub-mesoscale eddies near straits.

## TRANSITIONS

None.



*Figure 3. Cross sections at the Mindoro Strait from (120.25E, 12.2N) to (121.0E, 12.2N) for time-averaged August 2007: (a) potential temperature (color; Celsius) and sigma-t (contours; kg/m<sup>3</sup>) for the **hold** bathymetry case, (b) salinity (color) and velocity magnitude (contours; m/s) for the **hold** bathymetry case, (c) same as (a) but for the **hnew** case, (d) same as (b) but for the **hnew** case.*

## RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (Arango) closely collaborates with A. Moore (data assimilation and adjoint-based algorithms) at University of California, Santa Cruz, B. Powell (data assimilation applications) at University of Hawaii at Manoa, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia

Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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